Intelligent methods, functions and apparatus for load handling and transportation mobile robots. Patent application

CROSS-REFERENCE TO RELATED APPLICATIONS

This patent application claims the benefit of the prior Swedish patent application N:o 0300001-5, filed Jan. 2, 2003, for the same invention

BACKGROUND OF THE INVENTION

The invention relates generally to intelligent methods, functions and apparatus for mobile robots in the form of autonomous vehicles and machines for load handling and transportation, based on laser-optic sensors for position determination and mapping of terrain, material volumes and other handling objects, obstacle detection and vehicle and implement control in loading and unloading operations.

Autonomous vehicles for handling and transportation of goods are widely used in indoor industrial applications such as factory and warehouse logistics. Intelligent functions such as handling objects recognition and loading normally require palletised or otherwise standardised packaging. There is a need for intelligent autonomous vehicle handling and transportation functions also for bulk material such as heavy chemical and mineral products in indoor as well as outdoor applications. For other outdoor applications such as large scale earthmoving in mining and excavation, there is an increasing demand for autonomous excavators, front shovels and the like. In this field, there exists solutions based on electro-optic sensors and satellite navigation systems for recognising and acquiring bulk material such as minerals, ores and gravel.

In less extensive industrial applications, such as handling of solid fuels like biomass and coal and other products from forest and agriculture, there is a need for reliable, accurate, and cost effective technology. For these applications, the present technology for the extensive outdoor applications has some severe limitations. Many intelligent functions, such as navigation and handling object recognition and loading, are very dependent upon the continuous availability of accurate, real time, position determination information. Satellite position determination systems and its radio communication might get lost near buildings or through building walls. In order to back up satellite navigation, additional support technologies have to be installed on the vehicles and in the local environment such as inertial navigation systems and earthbound satellite transmitters, which leads to complicated and expensive system solutions at the risk of degraded reliability. The accuracy in position determination, particularly concerning the vertical "z" di-

mension and the pitch and roll angles of the present outdoor earthmoving technology is also not sufficient for controlling loading operations where the z-coordinate of material volume and the underlying ground surfaces is of great importance. Thus there is a need for a more accurate, practical and simple single system solution for main autonomous vehicle intelligent functions such as work area and mission planning and control, navigation, material volume acquisition and obstacle detection and suitable for limited industrial sites that works well in outdoor as well as indoor or mining environments.

The publication No. WO 87/02484 from 1987 mentions a driverless vehicle having a certain capability for autonomous loading and unloading of singular solid objects. The method requires each handling object to be provided with a number of reflectors. It is also required that the objects are made in standardised measures. The method is not capable of bulk material loading or loading solid objects of varying and unknown shape.

In US patent 5,548,516 from 1996 a driverless vehicle is described. This vehicle is capable of autonomous navigation based on GPS, inertial navigation and odometer based dead reckoning and it is equipped with a scanning laser rangefinder for obstacle detection and avoidance. The system has no dynamic terrain model and is lacking functions for autonomous material handling.

In a US research report:"Motion Planning for All-Terrain Vehicles: A Physical Modeling Approach for Coping with Dynamic and Contact Interaction Constraints", IEEE Transactions on Robotics and Automation, Vol 15, No 2, April 1999, a path planning concept is presented for a mobile robot moving in unlimited terrain. The concept is based on full á priori knowledge of the terrain topology, and problems related to material and load handling are not treated in this work.

Neither is load handling and transportation treated in another research publication, Autonomous Robot Navigation in Unknown Terrains: Incidental Learning and Environmental Exploration", IEEE Transactions on Systems, Man and Cybernetics, Vol 20, No 6, Nov/Dec 1990. This paper primarily deals with the problem of how to map the environment by means of a vehicle based terrain sensor.

In US patent 5,974,352 a method is given for controlling a bucket by means of sensors for lift and tilt cylinder position and pressure, and how to optimize bucket lift and tilt movements based on integration of forces and movements in the load handling implement. The method requires an on board human operator for selecting loading point and for driving the vehicle to

and from this point and who drives the vehicle in the entire loading movement and controls the bucket in the initial and final phases of the loading movement.

In US patent 6,173,215 methods are given for autonomous navigation of a vehicle upon detecting an obstacle. Obstacle detections are only handled in a fixed to vehicle coordinate system and in real time and not recorded in a fixed to ground coordinate system in order to be considered in the forthcoming path.

In US patent 6,223,110 B1, a software architecture is given for autonomous earthmoving machinery. The described application is centered around digging and excavation, and applications such as wheel loaders are only mentioned but not dealt with in any further detail.There is no reference to any work concerning how to solve the position determination problems especially concerning the z-coordinate in limited industrial environments, or how to measure, with satisfactory accuracy, the shape, volume and position of material volumes and other general handling objects in such environments. The problem of how to efficiently load and unload, with an autonomous vehicle, industrial products temporarily stored on surfaces that may not be horisontal or how to organise work in a limited areas is thus not dealt with in the patent or in its referenced publications.

Accordingly, the present invention is directed to overcome one or more of the problems set forth above.

BRIEF SUMMARY OF THE INVENTION

This invention solves some of the above presented problems, in autonomous vehicles and machines with load handling implements and systems for autonomous navigation within limited sites, by defining for such a site a number of well defined zones for loading, unloading and autonomous navigation, by means of establishing a dynamic terrain model for the worksite, including a layer defining each type of zone, and, in addition, layers for reference ground surface, a best estimate of total terrain surface and a developing terrain surface estimate by employing a simple and cost effective system with a few on board sensors for vehicle position determination and terrain surface measurement, where the principal elements of this system comprise a combination of a scanning laser rangefinder and an on board vehicle six degrees of freedom laser-optic position determination system, where a specific DTM (dynamic terrain model) computer analyses current measurements with respect to existing model values and thereby is able to detect and with high accuracy record and analyse the surface of terrain, material volumes, general handling objects and obstacles in the present position and predicted path of the vehicle,

where the position determination system determines the position of the vehicle and the scanning laser rangefinder in three dimensions and six degrees of freedom in a fixed to ground coordinate system and in addition provides position data for the steering control of the vehicle and also enables the continuous creation and updating of the above mentioned dynamic terrain model to be unambiguously performed in a fixed to ground coordinate system, and whereto a specific on board vehicle mission computer, based upon attack point and loading height profile data in a loading operation or bucket emptying point in an unloading operation from the DTM computer, this mission computer optimizes necessary parameters for the vehicle's path and the load handling implement's movements during approach, loading paths or unloading movements in an unloading operation, and where this mission computer also coordinates and demands vehicle path and implement movements both in previously fully planned and therefore static paths and movements as well as in the dynamically planned paths and movements the parameters of which have been calculated in the mission computer based on the analyses in the DTM computer.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

FIG. 1: Concepts tree. Relations between the concepts of driverless and autonomous and, in addition, preplanned versus intelligent and subconcepts to the latter.

FIG. 2: Load handling and transportation autonomous vehicle **1** with load handling implement **14** and bucket **142**, scanning laser rangefinder **81** for measuring the position of points on terrain surface, material volumes and obstacles for providing input data to the on board dynamic terrain model. Position determination system **7** with onboard rotating laser-optic sensor **71** and suitable groundbased reflectors **72**. The figure displays, in a vertical section, a laser ray being reflected by a material volume *181* and measuring the position of point P located in front of the vehicle **1**.

FIG. 3: Principles for a laser-optic position determination system according to Swedish patent nr 464 837 for determining, in a fixed to ground coordinate system *41*, the position of a vehicle **1** in three dimensions along with its heading, pitch and roll angles from angular measurements in a fixed to vehicle coordinate system *42* to a number of fixed to ground reflectors **72** within range of the rotating laser-optic sensor **71**.

FIG. 4: Determining the 3D position (X, Y, Z), in a fixed to ground coordinate system *41*, of points on the surface of terrain, material volumes and obstacles, from an arbitrarily posi-

tioned and oriented vehicle **1** employing an on-board scanning laser rangefinder **81** measuring in a fixed to vehicle coordinate system *42*.

FIG. 5: Terrain map, from a dynamic terrain model, representing a variable Z as a function of horisontal coordinates X and Y in a fixed to ground coordinate system.

FIG. 6: Area with borders drawn for a material volume *181* subject to be loaded from by the system and including an obstacle-free zone *191* and zones for reconnaissance *192* and loading *193,* respectively, an in preplanned reconnaissance path *111*, a dynamically planned approach path *121* from a first switch point *1112* reconnaissance/approach path to a dynamically planned vehicle loading point *1221*, the location for a dynamically planned switch point from approach to dynamically planned loading path *122* with its constituent dynamically planned movements of the load handling implement including the bucket, a dynamically planned transport path *124* governing the vehicle's **1** exit movement from the material volume and back to the waiting position *110* for change of direction backwards/forwards and static transport paths *112* to and from a vehicle unloading point *1231* with the constituent bucket movements required at unloading and exit from the unloading operation.

FIG. 7: Area with borders drawn for a material volume *181* subject to receive material in an unloading operation from the system and including an obstacle-free zone *191* and zones for reconnaissance *192* and unloading *194,* respectively, a preplanned reconnaissance path *111*, a dynamically planned approach path *121* from a first switch point *1112* reconnaissance/approach path to a dynamically planned unloading point *1231*, and the related position *1232* of the bucket at unloading with its constituent dynamically planned movements of the load handling implement including the bucket, a dynamically planned transport path *124* governing the vehicle's **1** exit movement from the material volume and back to the waiting position *110* for change of direction backwards/forwards. Static transport paths *112* for transports in an out of the area are also indicated.

FIG. 8: Block diagram with essential to the invention environment sensors and computers required on board the vehicle, including

- forward-looking scanning laser rangefinder **81** detecting and measuring, in a fixed to vehicle coordinate system, points on the surface of terrain, material volumes and on existing obstacles,

- position determination system **7** yielding, in a fixed to ground coordinate system, the position of the vehicle in six degrees of freedom: coordinates x, y and z and attitude angles ψ (heading), ϑ (pitch) and φ (roll),

- the DTM-computer **82** for updating, maintaining and analysing the dynamic terrain model DTM where this computer, based on the measurements from the scanning laser rangefinder **81** and the six degrees of freedom position updates from the position determination system **7** computes coordinates in the fixed to ground coordinate system for points on the surface of terrain, material volumes and on existing obstacles, employs these coordinates for updating and maintaining the dynamic terrain model DTM and by analysing this model computes and delivers to the mission computer **6** coordinates far loading and unloading points and a loading height profile data for planning loading paths and implement movement parameters by loading from respectively unloading to a material volume or unloading pocket and where this DTM-computer also evaluates criteria for emergency actions e.g. at incident obstacles, rejected path plans etc. and in such cases sends the corresponding obstacle detection message **984** messages to the vehicle control computer **211**,

- the mission computer **6** in control of the mission program, for dynamic planning of vehicle paths and the detailed movement of the vehicle along these paths as for planning the movements of the bucket in loading/unloading operations, and during transit movements and sends mission specific and dynamic command data to the DTM-computer **82**. The mission computer also furnishes the DTM-computer and the vehicle control computer **211** with vehicle control data lists **971** for steering and controlling the vehicle and its load handling implement,

- the vehicle control computer **211**, based on the vehicle control data lists **971** from the mission computer **6** or directly on any obstacle detection message **984** as obtained from the DTM-computer **82**, steering and controlling the vehicle and the load handling implement in autonomous mode by means of a number of actuators and sensors installed in the vehicle's control system. In remote mode the vehicle is controlled directly by an operator via radio link and the vehicle control computer,

- radio link **5** with radio link terminal **51** at operator station **3** and on board vehicle radio link terminal **52**, for sending mission instructions to the mission computer **6** and for incidental commands and remote control signals to the vehicle and, in addition for returning status information and position data from the vehicle to

- operator station **3** with MMI (man/machine interface) computer **31**,

- operator commanding and being provided with means for planning autonomous missions and, in exceptional or emergency case, for manual vehicle steering e.g. remotely via radio link.

FIG. 9: Dynamic approach path *121* with an inital set of a pair of clotoids and a circular path segment in between, followed by a straight path segment and finally again a pair of clotoids and a circular path segment in between.

FIG. 10: Flow and exchange of mission instructions and lower level messages and analysis and optimization tasks during reconnaissance and loading parts of a mission. Sample scenario.

FIG. 11: Load handling implement **14** with bucket **142** and elements of the vehicle's **1** mechanical framework. Skeleton model.

FIG. 12: Simplified model, built from rigid elements and pivot points, representing the mechanical structure of load handling implement **14** with bucket **142**

FIG. 13: Dynamic loading path *122*, shown as its projection on a fixed to ground coordinate system *41* x/y-plane, attack point *1222* for first entry of bucket in a material volume at loading, penetration depth $s(i)$ for each index $i = 0,1,2,3,...$, and estimated averages $Z_{load}(i)$ for the height in fixed to ground coordinate system *41* for points on the surface of the material volume *181* along a linear element having a length equal to the width of the bucket and being oriented perpendicular to the direction of the loading path.

FIG. 14: Cut-out volume, visualised in a fixed to ground coordinate system *41* with a polygon section model of the bucket **142** in a sequence of positions at states $k = 0, 1, 2, 3, ...$ of a conceptual loading process penetrating a material volume *181*.

FIG. 15: Bucket's volume holding capacity visualised for two different bucket positions

FIG. 16: Terrain profile from current real terrain *17* with ground surface *171*, material volume *181,* and obstacle *182*. Layer 1 drawing showing terrain profile from developing model from the vehicle's current running, layer 2 drawing showing profile of reference ground surface, current best estimate, layer 3 drawing showing profile of current best estimate of total terrain, difference $Z(1,n) - Z(2,n)$, drawing showing profile of height above reference surface as calculated from developing and reference estimates.

FIG. 17: Fixed to ground projection of vehicle **1** and its obstacle avoidance mapping *1955* in the dynamic terrain model.

DETAILED DESCRIPTION OF THE INVENTION

General

In the sequel the short notation of system is used for device, equipment, method or procedure or a combination of device or equipment and method or procedure.

With reference to the conceptual tree in FIG 1 and its explanation below the invention concerns intelligent functions for controlling autonomous vehicles, machines and their implements based on laser-optic sensors for position determination and mapping of terrain, material volumes, and obstacles.

The expression remote control is used for a system where a vehicle more or less continuously is controlled by an operator via a communication medium, normally such as a radio link while physically seeing the vehicle and its working site or possibly by using a video link from a camera on board the vehicle but where such operator is working outside the vehicle.

The word autonomous is used in its regular meaning as independent and something capable of operation without outside control. It refers to an executing activity being either fully automatic or at least mainly automatic, that is with a human operator only being needed in exceptional and emergency situations. An autonomous vehicle must be capable of operating unmanned, that is without needing any human driver or other operator, be it on board or at some remote operator station, for controlling the vehicle and for maneuvering its implements. If human passengers are carried on board, where these passengers are not involved in steering or otherwise controlling the vehicle except for intervening in exceptional cases or in emergency situations, such a vehicle can still be called autonomous.

The expression preplanned control is employed for autonomous operation following an á priori produced plan but with quite limited or no provisions for reactions and making corrections in real time in order to meet changes and unexpected situations.

The word intelligent is employed for a system for autonomous operation which differs from preplanned controlled autonomous operation in that it is provided with means and elements for modeling and estimating variable states of nature, as well as means that based on these models and parameter estimates generates, simulates and evaluates alternative operation execution plans, modifies preliminary plans or creates new plans for the operations according to some optimality criteria for assuring that the chosen plan, with available means and resources and within given constraints such as costs of operation and available time, is expected to yield more and better production than other candidate plans. As with preplanned control, an intelligent system also has elements for pursuing the current planning by proper employment and control of available resources for the purpose of the system.

Description of the invention

With reference to FIGs 2, 3, 4, 5, 6, 7, 8, 16 and 17 the invention concerns procedures in the form of intelligent functions for autonomous vehicles and machines employed in loading, unloading and transportation, based on mapping of terrain comprising reference surface, material volumes and obstacles and on such information based functions for autonomous vehicle path generation and vehicle and implement movement planning and control and for obstacle detection with autonomous emergency action. The invention comprises thereby;

- procedures for mapping a work site and its terrain surface comprising general handling objects *180*, material volumes *181* and obstacles *182* by means of;

- on board vehicle 1 sensors where such a vehicle is provided with a position determination system 7 with an on board vehicle rotating laser-optic sensor 71 for accurate position determination of the vehicle in three dimensions X, Y and Z in a fixed to ground coordinate system *41* and in addition heading, pitch and roll angle, by utilising fixed to ground reflectors 72 and;

- a system 8 for measuring, modeling and analysing terrain, material volumes and obstacles where this system comprises a scanning laser rangefinder 81 and a dynamic terrain model 821, DTM, in a terrain model- or DTM-computer 82 for the purpose and provided with algorithms for measuring, and recording terrain surface, material volumes and obstacles and, based on this during a mission more or less continuously collected information and prior mappings of the area, at autonomous loading and unloading of material inside for the purpose enclosed areas optimize coordinates for nearest or otherwise most optimum attack point *1222* for loading where the center of the forward edge of the loading bucket 142 can begin its penetration of the material volume, and to estimate, for the purpose of controlling the load handling implement 14, a height profile for the material volume along the intended path of the bucket during the loading path and movement of vehicle and bucket, and correspondingly at unloading to optimize coordinates for most distant or otherwise most optimum emptying point *1232* for the bucket and;

- by detection and in dangerous vicinity of any obstacle to prompt warning or emergency stop action, where the DTM-computer's reconnaissance and obstacle detection assignments are given from a;

- mission computer 6, which for the execution of a specific mission has been provided, by radio link data sent from an operator station 3 with mission instructions 9 comprising mission program 91 for the superficial vehicle control in a mission and parameters 92 for static

path *11* elements and prototype parameters **930** for the mission's dynamic path *12* elements
and reconnaissance assignment **94** with defined zones and reconnaissance directions, load-
ing, unloading and obstacle detection assignment **95** with border polygon list **951** for obsta-
cle free zones *191* and border polygon list **952** with obstacle detection geometries and action
parameters *195* for the vehicle and where this mission computer receives messages from the
DTM-computer concerning coordinates and local terrain model for loading and unloading
points, respectively, and by means of programs **611 - 613** for optimizing vehicle's path and
vehicle's and load handling implement's movement, and program **614** for simulating and
listing control data list **971** for controlling the path and movements of vehicle and load
handling implement and sends this data list to;

- a vehicle control computer **211** for the current path where this vehicle control computer via
  interface **212** to the electric and hydraulic systems of the vehicle controls the vehicle and its
  implement in thus dynamically planned paths and movements and on obstacles found by the
  DTM-computer and on direct obstacle detection messages **984** from this computer depend-
  ing on the vicinity to the obstacle reduces vehicle speed or, like in case of interrupted radio
  communication **5** with the operator station, halts the vehicle and alarms for operator inter-
  vention.

With procedures in the form of intelligent functions for autonomous vehicles and ma-
chines based on laser-optic sensors for position determination and mapping of terrain,
general handling objects, material volumes and obstacles and vehicle and implement con-
trol, the vehicle **1** is provided with a load handling implement **14** which includes a bucket
142 or other controllable implement for handling and carrying loads. For planning, moni-
toring and intervening the vehicle's operations there is an operator station **3** with
man/machine interface (MMI) computer, **31**, being provided with radio link **5** for com-
munication with the vehicle's mission computer **6**. The MMI computer can be provided
with a number of preplanned mission instructions **9** each comprising one for each mission
specific mission program **91** for distributing tasks and assignments to various subsystems
on board and for controlling, during mission execution, that these tasks and assignments
are carried out according to plans and where this mission program returns the initiative to
the operator station when the mission is completed or if it is by any other reason inter-
rupted. In the mission instruction there are also parameters **92** for static paths *11*, proto-
type parameters **930** for dynamic paths *12*, reconnaissance assignment **94** with, reconnais-

sance zone, border polygon list and reconnaissance direction **941**, loading zone, border polygon list and loading direction **942,** and unloading zone, border polygon list and unloading direction **943** and obstacle detection assignment **95** with obstacle free zones *191*, border polygon list **951** and vehicle's obstacle detection geometries *195* and action parameters **952**. In order to initiate such a mission, mission instructions **9** are sent from operator station **3** to the vehicle's mission computer **6** via radio link **5**.

In the total system there is a position determination system **7**. This is employed for vehicle **1** navigation, and provide position and attitude angles in a fixed to ground coordinate system *41* for a fixed to vehicle coordinate system *42* to applications such as coordinate conversion of data from a fixed to vehicle scanning laser rangefinder **81** belonging to on board vehicle subsystem **8** for detecting and measuring terrain surface, any general handling object *180,* material volume *181* and any obstacle *182*. The position determination system delivers in a fixed to ground coordinate system *41*, vehicle position in six degrees of freedom, being x-, y- and z-coordinates and the three attitude angles ψ (heading angle), ϑ (pitch angle)and φ (roll angle). In the fixed to ground coordinate system the X-axis can be defined as one towards north oriented vector in the horisontal plane, the Y-axis as a vector also in the horisontal plane, perpendicular to the X-axis and oriented to east. The Z-axis is a perpendicular vector to the same horisontal plane and perpendicular both to the X-axis and the Y-axis and oriented upwards, towards zenith. The fixed to vehicle coordinate system *42* is also a right angular coordinate system, its ξ-axis can be defined to be oriented in a forward direction along the full length direction of the vehicle, the η-axis oriented in the vehicle's athwart direction and the ζ-axis upwards and perpendicularly to both the ξ-axis and the η-axis. The fixed to vehicle coordinate system's position and orientation in space is defined by the position (x,y,z) for its origo and its rotations in the fixed to ground coordinate system are defined by the three attitude angles ψ (heading angle), ϑ (pitch angle)and φ (roll angle). The angle ψ can now be defined as a clockwise rotation of the fixed to vehicle coordinate system around its own ζ-axis, as seen from a point on the positive part of this ζ-axis. In the same way the angle ϑ is defined as a counter clockwise rotation of the fixed to vehicle coordinate system around its own η-axis, as seen from a point on the positive part of this η-axis, and the angle φ as a counter clockwise rotation of the fixed to vehicle coordinate system around its own ξ-axis, as seen from a point on the positive part of this ξ-axis.

Such a position determination system 7 can be set up according to the procedures given in US patent nr 5,242,481 and which, in order to obtain six degrees of freedom in position determination performs angular measurements in azimuth and elevation to a number of fixed to ground reflectors 72.

The present invention is a further development from this US patent through employment of a forward looking scanning laser rangefinder 81, for the purpose of with high precision detecting and measuring the terrain, material volumes and other objects such as obstacles in front of the vehicle, and its associated DTM-computer 82 for the purpose of converting, based on the six degrees of freedom data from the position determination system 7, the measurements from the scanning laser rangefinder into coordinates in the fixed to ground coordinate system *41* for points on the terrain surface, on material volumes *181* and on occurring obstacles *182*, and by these means build up and a dynamic terrain model DTM 821. Based on such a DTM various analyses can be performed enabling dynamic planning of the vehicle's 1 movements such as the optimization of coordinates for target points and path layouts for the vehicle's movement in loading and unloading tasks, and for optimization of parameters for movements of the vehicle's and its implements in such loading and unloading operations. In addition, the DTM can be used for detecting, inside obstacle free zones *191*, any occurring obstacles and to prompt suitable reactions.

Furthermore the vehicle 1 is arranged for autonomous operation by being provided with a vehicle control computer 211 with interfaces 212 to the vehicle's electrical system, including engine, gearbox, main brake, parking brake, and vehicle steering system, and interfaces to the load handling implement's 14 sensors and actuators, interface to a position determination system 7, interface to the operator station 3 via radio link 5, interface to the mission computer 6 and, for obstacle avoidance functions also an interface to the DTM-computer 82 with its digital terrain model 821.

The main action of the vehicle control computer 211 is based on the vehicle and implement control data list 971 which is dynamically generated by the mission computer 6 by means of a program 614 for simulating and producing a time sequential listing of control variables such as coordinates for the path of the vehicle, heading angle and speed for the movement of the vehicle and actuator positions, engine rpm and hydraulic pressure levels for the movement of the load handling implement 14. Such a list is produced for each path from one point to another on the path where such a point either is a point where the vehicle is standing still for a moment or a specified switch point where the vehicle's control is

intentionally switched from one vehicle and implement control data list to another without neccessarily requiring the vehicle to stand still. For a static path *11* the vehicle and implement control data list is generated in the mission computer from a set of prepared parameters **92** for static path, while for a dynamic path *12* the vehicle and implement control data list is generated from a set of parameters **931** dynamically optimized by a program in the mission computer **6**. For this purpose, programs for optimization of approach, loading paths and unloading movements **611, 612,** and **613,** respectively, are used along with both a set of prototype parameters **930**, and a set of measurements and data from the DTM-computer **82** in the form of detection, loading path and unloading point messages **981, 982,** and **983,** respectively.

In the DTM-computer **82** there is a dynamic terrain model DTM **821** which covers the entire work site with transport routes and zones for reconnaissance *192*, loading *193* and unloading *194*. The DTM computer receives, continuously during the mission, position data from the position determination system **7**. By means of from the position determination system obtained coordinates and attitude angles, in the fixed to ground coordinate system *41* for a six degrees of freedom position of the fixed to vehicle coordinate system *42*, the laser rangefinder **81** measurements are transformed from this fixed to vehicle coordinate system, to positions in the fixed to ground coordinate system for updates of the DTM. Via the mission computer **6** the DTM computer is provided with suitable zone border polygon lists **941, 942** and **943** for reconnaissance *192*, loading *193*, and unloading zones *194*, respectively, as provided in mission instruction **9**. Based on these data a criterion is evaluated in the DTM computer to decide when the vehicle is inside reconnaissance zone whence this computer commences to actively update, by using range and angle measurements from the scanning laser rangefinder **81**, the DTM **821** inside the current loading or unloading zone.

During a loading or unloading operation a reconnaissance path *111* is inserted after some initial static paths possibly required in order to get the vehicle sufficiently near the current loading or unloading zone. During the reconnaissance path the objective is to detect a feasible point, the attack point *1222* on the material volume *181* where the bucket **142** can start to penetrate during a dynamic loading path *122* with its constituent movements of vehicle and bucket or a feasible location, the bucket emptying point *1232* with its constituent movements of vehicle and bucket.

In parallell with the above DTM **821** updating process the DTM computer **82** also analyses a developing part of the DTM as updated by the incoming measurements when advancing in the reconnaissance path in order to find, in a loading operation, by means of a specific algorithm **824** for optimizing the attack point *1222* position, the nearest or otherwise most optimal attack point, or, in an unloading operation, by means of a specific algorithm **826** for optimizing the bucket emptying point *1232* position, the most distant or otherwise most optimal point. As soon as the optimal coordinates of such a point *1222* or *1232* has been found the DTM computer sends, to the mission computer **6**, a detection message **981** with coordinates for the vehicle's **1** current position and coordinates for the optimal attack or unloading point. In the mission computer can then be obtained parameters for a dynamic approach path *121*, by means of mission computer program **611** for approach path optimization, based on the arriving data from the DTM computer and also on prototype path parameters **930** in mission instruction **9**. This dynamic approach path, as defined by parameters **9311**, vehicle and implement control data list **971**, and switch point reconnaissance/approach path *1112* for finishing the current reconnaissance path *111*, leads the vehicle to a suitable position, vehicle loading point *1221* representing the position of the vehicle in front of the attack point *1222* in a loading operation, or unloading point *1231* representing the position of the vehicle in front of the bucket emptying point *1232* in an unloading operation. The mission computer also sends a path switch message **972** with coordinates for the switch point and approach path vehicle and implement control data list to the vehicle control computer **211**. The mission computer also sends a report point *1211* message **973** to the DTM computer with coordinates for the point on the path where the DTM computer shall deliver, to the mission computer in a loading operation, a loading path message **982** with estimated coefficients **9821** for an analytic approximation of the ground surface at the vehicle loading point and a loading height profile data list **9822** with z-coordinates for points on the material volume *181* surface along the loading direction from the attack point *1222*, or in an unloading operation a vehicle unloading point message **983** with estimated coefficients **9831** for an analytic approximation of the ground surface at the unloading point and a vehicle unloading point local terrain model parameter list **9832** for a local terrain model of the material volume around the bucket emptying point *1232*. The DTM-computer analyses the developing DTM in order to perfect the coefficients and parameters required by the mission computer. When, in a loading operation, the report point has been reached and the loading path message **982** has

been sent over from the DTM computer the mission computer then optimizes the loading path *122* parameters **9312** based on the received message data, and loading path prototype parameters **9302** in the mission instructions **9**. This optimization is done by means of program **612** for loading path and its constituent bucket movement optimization. In an unloading operation, when the unloading point message **983** has been sent over from the DTM computer, the mission computer then optimizes the unloading movement parameters **9313** based on the received message data, and unloading operation prototype parameters **9303** in the mission instructions **9**. This is done by means of program **613** for unloading bucket movement optimization.

When in this way the valid parameters for loading or unloading vehicle path and vehicle and implement movements are available, before actually being carried out, these movements are simulated in the mission computer by means of its vehicle path and load handling implement movement simulation algorithm **614**. By this simulation, a new vehicle and implement control data list is generated which then is sent to the vehicle control computer. This computer switches its control of the vehicle and its implements from the approach path to the loading path or unloading movement according to the received data upon arrival to the vehicle loading point *1221*. Finally, the vehicle's advancing movements are retarded and brought to finish, while the bucket **142** is allowed to perform its proper movements as planned for the loading or unloading operation in question. When even these movements are finished, the vehicle control computer requests, for the return path *124* and its constituent bucket movements, a new vehicle and implement control data list from the mission computer. The mission computer then optimizes the return movement parameters for a path to some point where the mission can be further continued according to the mission program **61**, based on the actual position of vehicle and implements in the finished loading or unloading movements, and if from a loading operation also based on prototype parameters **9304** for a dynamic return transport path *124*.

During all operations with an autonomous vehicle or machine **1** according to this invention, another duty for the DTM computer **82** is to compare currently received measurements from the scanning laser rangefinder **81** with the already available dynamic terrain model when in the obstacle free zone *191*, and also to continuously evaluate criteria for obstacle detection or any possible intrusion of the vehicle or machine outside the obstacle free or loading or unloading areas.

<u>Measuring terrain comprising reference surface, general handling objects, material volumes and obstacles</u>

The scanning laser rangefinder **81** ought to be installed relatively high on the vehicle **1**, cf FIG 2, such as on the forward edge of the vehicle's cabin roof, forward oriented and in addition inclined downwards. The laser light is pulsed and its time of flight to reflection and back to the receiver is employed for the distance measurement. The laser rangefinder is scanning in azimuth by means of a rotating mirror. This way, the laser rays are sent out in a plane parallell to the η-axis of the fixed to vehicle coordinate system **42** but with a perpendicular to the plane tilted forwards in the ξ - ζ - plane with an angle β from the ζ-axis. The laser rays will hit the terrain in a sequence of points and as seen in a cross section in the point P (FIG 2). The scanning laser rangefinder **81** measures distance R to a reflection and angle α, cf FIG 4, in the inclined plane where this angle is defined of a) the abovementioned vehicle ξ-axis and b) by the instantaneous vector orientation of the laser ray.

The coordinate vector $\mathcal{X} = (\xi, \eta, \zeta)$ for the position in the fixed to vehicle coordinate system **42** for each such point P can now be obtained by means of these measurements α and R, the scanning laser rangefinder's **81** position (ξ_0, η_0, ζ_0) in the fixed to vehicle coordinate system and the scanning laser rangefinder tilt angle β from the ξ-axis:

$$
\left.
\begin{aligned}
\xi &= \xi_0 + R\,\cos\alpha\cos\beta \\
\eta &= \eta_0 + R\,\sin\alpha \\
\zeta &= \zeta_0 + R\,\cos\alpha\sin\beta
\end{aligned}
\right\} \tag{1}
$$

With these coordinates in the fixed to vehicle coordinate system **42** and by employing the six degrees of freedom position data from the on board position determination system **7** the coordinates of the scanning laser rangefinder's measured point P can now be obtained in the fixed to ground coordinate system **41**. The six degrees of freedom position determination from system **7** comprises the $\mathbf{X} = (X, Y, Z)$ and the attitude angles ψ, ϑ and φ, the latter needed for the transformation matrix $\mathbf{M}(\psi, \vartheta, \varphi)$:

$$
\mathbf{M}(\psi, \vartheta, \varphi) =
$$

$$
= \begin{bmatrix}
\cos\psi\cos\vartheta, & \sin\psi\cos\vartheta, & \sin\vartheta \\
-\sin\psi\cos\varphi + \cos\psi\sin\vartheta\sin\varphi, & \cos\psi\cos\varphi + \sin\psi\sin\vartheta\sin\varphi, & -\cos\vartheta\sin\varphi \\
-\sin\psi\sin\varphi - \cos\psi\sin\vartheta\cos\varphi, & \cos\psi\sin\varphi - \sin\psi\sin\vartheta\cos\varphi, & \cos\vartheta\cos\varphi
\end{bmatrix} \tag{2}
$$

The $\mathbf{X_{las}} = (x_{las}, y_{las}, z_{las})$ in the fixed to ground coordinate system **41** for the point P can now be obtained as:

$$
\mathbf{X_{las}} = \mathbf{X} + \mathcal{X} * \mathbf{M}(\psi, \vartheta, \varphi) \tag{3}
$$

This way, each measurement with the scanning laser rangefinder **81** results in a three dimension coordinate determination in the fixed to ground coordinate system *41*. The calculations of equations (1), (2) and (3) are made in the DTM-computer **82**, and the obtained coordinates are first compared with the current dynamic terrain model **821** in the DTM-computer, such as for detecting a new obstacle, and finally for updating the dynamic terrain model.

Such a terrain model **821** can be based on a square grid. With a square mesh side length of d = 0.33 m an area of 100,000 m² is covered by roughly one million squares. If for each square is stored 32 byte index, Z-value, age of data and accuracy measure in the dynamic terrain model **821** a storage space of 32 Mbytes is required in the DTM-computer **82** for this model allowing a resolution of some 1/64000 in the Z variable. Let a square be identified as (i, j) when its four corners has the coordinates in plane X/Y:

lower left corner:	$(i-1, j-1)d$	(4a)
lower right corner:	$(i-1, j)d$	(4b)
upper left corner:	$(i, j-1)d$	(4c)
upper right corner:	$(i, j)d$	(4d)

The centre point of a square identified as (i, j) has the coordinates in plane X/Y:

$$\begin{cases} X_i = (i - 0.5)d, & 1 \le i \le imax \\ Y_j = (j - 0.5)d, & 1 \le j \le jmax \end{cases} \qquad \begin{matrix}(5a)\\ \\ (5b)\end{matrix}$$

Each measurement X_{las} can then be computed with or update the terrain model **821** in the square (i, j) where these indexes i and j are determined by the inequalities:

$$\begin{cases} (i - 1)d < X_{las} \le id \\ (j - 1)d < y_{las} \le jd \end{cases} \qquad \begin{matrix}(6a)\\ \\ (6b)\end{matrix}$$

The dynamic terrain model DTM **821** is required to be defined in every point of an entire work site be it for comparisons with fresh measurements (obstacle detection), or be it for optimization of coordinates **9811** and **9812** for attack point *1222* or bucket emptying point *1232* and for optimizing loading path *122* and unloading movement *123* where such optimizations require estimations of loaded volume or available volume for unloading material for various sets of parameters for these movements. Some parts of the DTM can be prepared before a mission is executed while others are based or updated also in important layers from earlier measurement runs with vehicle and its sensors. To each square (i, j) in the DTM, $1 \le i \le imax$ and $1 \le j \le$ jmax an ordered sequence of numbers n can be defined in a way so that to each integer value n

corresponds unambiguously a certain model square (i, j) and to each model square (i, j) corresponds the same number n:

$$n = \begin{cases} i \cdot imax + j & \text{if } jmax \leq imax \\ i + j \cdot jmax & \text{if } imax < jmax \end{cases} \qquad (7a)$$

or the inverse:

$$i = \begin{cases} \text{integer part of fraction } n/imax & \text{if} & jmax \leq imax \\ n - j \cdot jmax & \text{if} & imax < jmax \end{cases} \qquad (7b)$$

$$j = \begin{cases} n - i \cdot imax & \text{if} & jmax \leq imax \\ \text{integer part of fraction } n/jmax & \text{if} & imax < jmax \end{cases} \qquad (7c)$$

Various layers can be employed in the DTM for separating different kinds of zones and data in the DTM. Cf FIG 16. The identification $Z(LAG, n)$ represents Z-coordinate i layer LAG for element n in DTM. In the sequel is employed:

• Layer 0. Index number n

• Layer 1. $Z(1, n)$ is a developing estimate based on measurements only from the vehicle's current running in the path for detecting and measuring the terrain surface including handling objects *180*, material volumes *181*, and obstacles *182*.

• Layer 2. $Z(2, n)$ represents the reference ground surface and is intended to be an actual best model estimation of the real ground surface without any handling objects, material volumes, or known and unknown obstacles.

• Layer 3. $Z(3, n)$ is intended to be a current best model estimation of the total site terrain surface and represents handling objects, material volumes and known obstacles for which the Z-values of the model elements are determined from measurements from earlier paths and operations on the site or otherwise provided fundamental data. It is also assumed that measurements from earlier unknown but after the detection physically removed obstacles have been cleaned away from those model squares once occupied by measurements from such currently removed obstacles.

• Layer 4. Obstacle-free zone *191* denotation field. $Z(4, n) = 1$ for obstacle free zone.

• Layer 5. Reconnaissance zone *192* denotation field. $Z(5, n) = 1$ for reconnaissance zone.

• Layer 6. Loading zone *193* denotation field. $Z(6, n) = 1$ for loading zone.

• Layer 7. Unloading zone *194* denotation field. $Z(7, n) = 1$ for unloading zone.

Measurements concerning element n can be stored in several ways:

- Last measured Z-value, written as Z_{-1} (L, n), is stored. Once stored, the value is written as Z_0 (L, n)

- A moving average from the last k measurements is stored and written also as Z_0 (L, n), that is

$$Z_0 (L, n) =[Z_{-1} (L, n) + Z_{-2} (L, n) + ... + Z_{-k} (L, n)] / k \qquad (8a)$$

- A recursive filter with the experimental filter coefficient γ, $0<\gamma<1$ is employed for updating the model value Z_0 (L, n) with the value Z_{-1} (L, n) from the last measurement. The filter can be initialised by: Z_0 (L, n) = Z_{-1} (L, n) the first time a measurement represents element n, subsequently the following recursive filter equation can be employed:

$$Z_0 (L, n) = \gamma Z_0 (L, n) + (1-\gamma)Z_{-1} (L, n) \qquad (8b)$$

This kind of method is suitable if a large number of measurements is expected for each element number n.

Criteria for DTM-based obstacle detection

Autonomous driving is allowed in obstacle free zones *191* and in loading *193* and unloading zones *194*. Obstacle free zones are only allowed outside loading and unloading zones. The objective of the DTM-based_obstacle detection function is to test for obstacle detection in element n the hypotesis that the criterion $H \le [Z(1,n) - Z(3,n)]$ holds for a minimum obstacle height H for each element n where $Z(4,n) = 1$ and where this element is located inside or within a specific neighbourhood of the vehicle in its current or planned and predicted position. Thus, if an obstacle is detected in element n of the DTM, $Z(4,n)$ is set to zero until the obstacle is removed. Employing the differences $Z(1,n) - Z(3,n)$ has the benefit, especially in cases of uneven terrain and reference surface, to produce more accurate measurements of obstacles. Cf FIG 16.

Creation and updating of material volume models

As the vehicle on reconnaissance path *111* enters reconnaissance zone *192*, cf FIGs 6 and 7, those measurements representing terrain model elements inside loading *193* or unloading *194* zone are used to create and update the developing layer 1 of the DTM model inside such a zone representing the material volume model. The purpose is primarily to collect fresh data for the currently forthcoming approach path *121*, loading path *122*, or unloading movement *123*. By storing model values to the next path or operation such a dynamic model can contain certain errors as the shape and size of the material volume *181* might have changed when it is going to be approached next time. On the other hand it would be of value if neighbouring loading or unloading zone elements not centrally involved in the previous run still have become updated in

the model during such a run to be used for e.g. planning further reconnaissance paths in this area.

Optimization of attack point *1222* and bucket emptying point *1232* coordinates

Several factors have to be considered when optimizing attack point *1222* position in a loading operation. It is important to select such attack points so that the remaining material does not risk to interfere with the return movements from a loading path *122*. For this reason strategies leaving an outward concave material volume front ought to be avoided even if such a strategy at first thought might appear attractive in order to minimize distance travelled. On the other hand a strategy producing an outward convex front would lead to unneccessarily long travel distances and require quite large areas for vehicle maneouvers. Therefore, a strategy leaving a straight front line is the natural choice. These factors are also applicable in unloading. This way, the material volume *181* can be attacked from one direction all the time thus considerably simplifying approach and exit path planning.

A method to get such a straight front line is, to select attack point *1222* or bucket emptying point *1232* on edges of the material volume *181* maximally deviating from such a straight front line. A straight line facing and parallell to the desired front line and located at some distance from the front can serve as reference. In a loading operation, attack points are chosen where the distance between the candidate point and this reference line is minimum. In an unloading operation, bucket emptying points are chosen where this distance is maximum. For the DTM **821** has been defined $Z(6,n) = 1$ to represent a situation where element n is in a loading zone *193* and $Z(7,n) = 1$ means that element n is in an unloading zone *194*.

Threshold levels Hload and Hunload representing least volume height worth loading from and maximum volume height worth filling to, respectively, are employed in order to avoid that too small spill heaps, material rests and unevenness would cause unnecessary work load.

Optimizing the coordinates of attack point and bucket emptying point

a) based on nearest or most distant point in the material volume as measured from a reference line

When the vehicle **1** in a loading operation, cf FIG 6, drives forward on reconnaissance path *111* and begins approaching a material volume *181* in a loading zone *193* measurements will commence regarding elements of DTM **821** inside the loading zone with a height above threshold level for loading, provided there is material enough to load. In order to avoid, in situations with a multitude of elements in the DTM suitable for loading, that only the first element that satisfies

the threshold criterion will be selected, it is required that the vehicle continues a given further distance after this event. The endpoint on this travelling distance can be defined as detection point *1111*. At this detection point it is possible that a multitude of elements have been recorded and can be employed for final selection of attack point *1222* for loading. If still only the first detected element has been recorded it is probably singular in a sufficiently large environment and can therefore be selected as attack point on good grounds in such a case. The detection event is defined as the moment when the vehicle arrives at this detection point.

For an unloading operation, cf FIG 7, a similar reasoning leads to a procedure for selecting bucket emptying point *1232*. A criterion for this point in unloading is that the vehicle **1** has moved a given further distance since the first occurrence of measurements representing elements in the DTM **821** where the element volume is measured not to allow further unloading, alternatively that the entire surface is empty, thus allowing the reconnaissance path to be aborted when the most remote border of the unloading zone *194* has been passed, with required margins, by the measurements of the scanning laser rangefinder **81**. The unloading can start at this most remote border.

At detection point *1111* the binary occupancy vectors $Q_{load}(n)$ and $Q_{unload}(n)$ can be defined as

$$Q_{load}(n) = \begin{cases} 0 & \text{if } [Z(1, n) - Z(2, n)] < H_{load} \\ 1 & \text{if } H_{load} \leq [Z(1, n) - Z(2, n)] \end{cases} \qquad (9a)$$

and

$$Q_{unload}(n) = \begin{cases} 0 & \text{if } H_{unload} \leq [Z(1, n) - Z(2, n)] \\ 1 & \text{if } [Z(1, n) - Z(2, n)] < H_{unload} \end{cases} \qquad (9b)$$

As attack point *1222* for loading and bucket emptying point *1232* at unloading can now be selected the coordinates for element $n = n_{load}$ and $n = n_{unload}$ when these points are most close and most distant, respectively, from a straight line, arbitrarily chosen to suit the purpose, cf "A- A" in FIGs 6 and 7, and where the elements n_{load} and n_{unload}, respectively, also satisfy the conditions:

for loading, requirement for n_{load}

$$\begin{cases} Q_{load}(n_{load}) & = 1 \qquad\qquad (10a) \\ Z(6, n_{load}) & = 1 \qquad\qquad (10b) \end{cases}$$

for unloading, requirement for n_{unload}

$$\begin{cases} Q_{unload}(n_{unload}) & = 1 \qquad\qquad (11a) \\ Z(7, n_{unload}) & = 1 \qquad\qquad (11b) \end{cases}$$

b) based on nearest or most distant point in a cell belonging to an ordered sequence:

In this alternative each element n satisfying $Z(6,n)=1$ or $Z(7,n) = 1$ belongs to an ordered sequence $N= 1,2,3,...$, NMAX of cells, where we take $\Gamma(N,n) = 1$ to indicate that element n belongs to cell N. At loading and unloading, to the condition pairs (10a), (10b) and (11a), (11b), respectively, are added the further conditions:

$$\Gamma(N, n_{load}) = 1 \qquad (10c)$$

$$\Gamma(N, n_{unload}) = 1 \qquad (11c)$$

where cell N is currently selected for loading/unloading.

Path generation at entering and exiting from a loading or unloading zone

A mission instruction **9** with loading or unloading operations has to be prepared with at least one preplanned static reconnaissance path *111*, for the vehicle **1** to follow while its sensors are scanning and analysing the material volume *181* from or to which loading or unloading, respectively, is desired, cf FIGs 6 and 7. During the vehicle's travel along this reconnaissance path, coordinates for an attack point *1222* or for a bucket emptying point *1232* are obtained at the detection point *1111*, as a result of the analysis in the DTM-computer **82** by means of the abovementioned conditions and criteria applied on the successively, during the vehicle's travel, developing $Z(1, n)$, $n = 1, 2, 3, ...$ of the dynamic terrain model **821**. At the detection event as-defined above, the DTM-computer sends a detection message **981** to the mission computer **6** with coordinates **9811** or **9812** for the selected attack point or bucket emptying point, respectively. It is now possible for the mission computer to determine the position of a switch point *1112* where the reconnaissance path can be finished and an approach path *121* can start, by knowing the amount of time required for the system to optimize, parameters **9311** for the dynamic approach path *121* and produce and send vehicle and implement control data list **971** to the vehicle control computer **211**. The approach path has to be designed to lead the vehicle to a position, the vehicle loading point *1221*, the position of the vehicle **1** when the bucket **142** starts penetrating the material volume *181* at the attack point *1222* or, in an unloading operation to a position, the unloading point *1231*, from which the vehicle can start some finishing maneouvers to be prepared for the unloading movement *123*. The coordinates (Xc, Yc, Zc) for the vehicle's position in the vehicle loading point can be obtained from the coordinates of the attack point by knowing the geometry of the vehicle and its load handling implement **14** and the actual loading direction ψc. Coordinates for the vehicle's position in a vehicle unloading point can be obtained in an analogous way.

As the selected loading or unloading point not always is located straight in front of the vehicle 1, the dynamic approach path *121* has to allow for, on the travel from the switch point *1112*, first a sideways translation of the vehicle, and second to guide the vehicle to the intended direction in the vehicle loading *1221* or vehicle unloading point *1231*. Thus a more or less s-shaped path is required. By employing, in path generation, a mix of clotoid, circular and straight path segments, where the clotoid segments will bring the path's radius continuously between straight path and least turning radius, a large variation of such paths can be designed in a manner which is contributing to limit steering errors. A simple two-dimensional path model of limited complexity that works well for this purpose, cf FIG 9, consists at its maximum of two bends with a straight path between. In the first bend the heading angle is changing the amount α_1, and α_2 in the second. Each bend consists of a pair of clotoids and, for large α_1 and α_2, a circular path segment inserted between bending and straightening clotoid. For a simple path without any obstacle, where start point and end point are given as three-dimensional coordinate vectors X_A and X_C and heading angles ψ_A and ψ_C respectively, a formulation of the problem can be reduced to three non-linear equations, one for X-coordinate, one for Y-coordinate, and one for heading angle ψ. A practical assumption is to optimize the path in the two dimensions X and Y only. The Z-coordinate of the path will then follow from the dynamic terrain model **821**. The following variables and equations are used:

$X_A = (X_A, Y_A, Z_A)$ and ψ_A are coordinates and heading angle in the fixed to ground coordinate system *41* for vehicle 1, in switch point *1112* reconnaissance/approach path

$X_C = (X_C, Y_C, Z_C)$ and ψ_C are coordinates and heading angle in the fixed to ground coordinate system *41* for vehicle 1 in loading *1221* respectively unloading point *1231*.

The three equations can be written

$$X_C - X_A = \sum_{k=1}^{7} X(k), \text{ vectorial equation in 3D} \qquad (12a)$$

$$\psi_C - \psi_A = \sum_{k=1}^{7} \psi(k) \qquad (12b)$$

where the three dimensional vector $X(k)$ and the angle $\psi(k)$ constitute the additive contribution in coordinates X and Y respectively heading angle ψ from each of the path segments No. k = 1, 2, 3,...,7.

Each one of the two bends of the assembled curve, consists of one bending and one straightening clotoid segment and has to include , if the total heading angle change α_i in bend number "i" amounts to more than a determined amount α_o, one between the two clotoid segments inserted circular segment with bending angle $\alpha_c = \alpha_i - \alpha_o$

The vector **klot**(M_i, S_i) is employed for the bending clotoid in bend No. i as a function of the parameter S_i and the clockwise/counterclockwise factor M_i

(clockwise, $M_i = 1$, counterclockwise, $M_i = -1$)

$$\textbf{klot}(M_i,\ S_i) = [\int_{u=0}^{u=S_i} \cos(u^2/2)\ du,\ M_i\int_{u=0}^{u=S_i} \sin(u^2/2)\ du] \tag{13a}$$

and the vector **cirk**(M_i, α_c) for the circular path as a function of its bending angle α_c and M_i

$$\textbf{cirk}(M_i, \alpha_c) = [\sin\alpha_c,\ M_i(1-\cos\alpha_c)] \tag{13b}$$

where

$$S_i = \begin{cases} \sqrt{\alpha_i} & \text{if} \quad \alpha_i < \alpha_o \\[2mm] \sqrt{\alpha_o} & \text{if} \quad \alpha_o \le \alpha_i \end{cases} \tag{13c}$$

The following 3D coordinate transformation matrix is employed.

$$M(\psi_i) = \begin{bmatrix} \cos\psi_i & -\sin\psi_i & 0 \\ \sin\psi_i & \cos\psi_i & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{14}$$

The contributions of each of the seven partial segments to the terms in equations (12a) and (12b) can now be stated. For the partial segments 1-3 and 5-7 the characters M_1 respectively M_2 for their clockwise/counterclockwise factors and the characters α_1, S_1 and α_2, S_2 for angles and arguments for their clotoid vectors.

Partial segment 1. Bending clotoid in the first path bend where A = scale factor, common for the entire curve.

$$X(1) = A \cdot \textbf{klot}(M_1,\ S_1) * M(\psi_A) \tag{15a}$$

$$\psi(1) = \begin{cases} 0.5M_1 \cdot \alpha_1 & \text{if } \alpha_1 \le \alpha_o \\[2mm] 0.5M_1 \cdot \alpha_o & \text{if } \alpha_o < \alpha_1 \end{cases} \tag{15b}$$

Partial segment 2. Circular. Omitted if $\alpha_1 \leq \alpha_0$

$$\mathbf{X}(2) = \mathbf{A} \cdot \mathbf{cirk}(M_1, \alpha_1 - \alpha_0) * \mathbf{M}(\psi_A + 0.5M_1 \cdot \alpha_0) \tag{16a}$$

$$\psi(2) = M_1 \cdot (\alpha_1 - \alpha_0) \tag{16b}$$

Partial segment 3. Straightening clotoid. Obtained by means of in two orthogonal directions mirroring the vector for bending clotoid from the point where the path transfers from clotoid to straight path

$$\mathbf{X}(3) = \mathbf{A} \cdot \mathbf{klot}(-M_1, S_1) * \mathbf{M}(\psi_A + M_1 \cdot \alpha_1) \tag{17a}$$

$$\psi(3) = \psi(1) \tag{17b}$$

Partial segment 4. Straight path, zero contribution to total heading angle increment. Segment travel length = LNGD·

$$\mathbf{X}(4) = (\mathrm{LNGD}, 0) * \mathbf{M}(\psi_A + M_1 \cdot \alpha_1) \tag{18a}$$

Partial segment 5. $\quad \psi(4) = 0 \tag{18b}$

Partial segment 6. Bending clotoid in the second path bend

$$\mathbf{X}(5) = \mathbf{A} \cdot \mathbf{klot}(M_2, S_2) * \mathbf{M} \ (\psi_A + M_1 \cdot \alpha_1) \tag{19a}$$

$$\psi(5) = \begin{cases} 0.5M_2 \cdot \alpha_2 & \text{if } \alpha_2 \leq \alpha_0 \\ \\ 0.5M_2 \cdot \alpha_0 & \text{if } \alpha_0 < \alpha_2 \end{cases} \tag{19b}$$

Partial segment 7. Circular. Omitted if $\alpha_2 \leq \alpha_0$

$$\mathbf{X}(6) = \mathbf{A} \cdot \mathbf{cirk}(M_2, \alpha_2 - \alpha_0) * \mathbf{M} \ (\psi_A + M_1 \cdot \alpha_1 + 0.5M_2 \cdot \alpha_2) \tag{20a}$$

$$\psi(6) = M_2 \cdot (\alpha_2 - \alpha_0) \tag{20b}$$

Partial segment 8. Straightening clotoid. Obtained by means of in two orthogonal directions mirroring the vector for bending clotoid at the endpoint of the total path where the heading angle is ψ_C.

$$\mathbf{X}(7) = \mathbf{A} \cdot \mathbf{klot}(- M_2, S_2) * \mathbf{M}(\psi_C) \tag{21a}$$

$$\psi(7) = \psi(5) \tag{21b}$$

The equation system (12), neglecting the Z-coordinate, is easily solved in the mission computer **6** by means of standard mathematical procedures for non-linear equation systems and using random start solutions in the relevant variables M_1, M_2, LNGD, α_1 and α_2. The resulting path can be used both for forwards and backwards driving.

Loading operation optimisation based on the dynamic terrain model and a model of the mechanics of the load handling implement

When the report point *1211* on the dynamic approach path has been attained and loading path message **982** from the DTM-computer **82** has been received by the mission computer **6**, message data is used for optimizing parameters for vehicle and implement control in the dynamic loading path *122*. For this purpose is used in the optimization, both the coefficients **9821** of ground plane at the vehicle loading point *1221* and the loading height profile data list **9822** with the table z(k), k=0,1,2,... for terrain height at successive points along the intended loading path when penetrating the material volume *181*, cf FIG 13. Loading path depth and velocity, and bucket **142** lift and tilt movement parameters are optimized considering the requirements and constraints of filling the bucket, such as cost, minimising time of operation, minimising ground friction from bucket, minimising material spill and keeping power requirements below available power train capacity.

Groundplane model for the vicinity around the loading point

For optimising the bucket **142** movements in the dynamic loading path *122* it is needed, for any advancement of the vehicle **1** along the intended loading path to be able to estimate a six degrees of freedom position in the fixed to ground coordinate system *41* of the fixed to vehicle coordinate system *42*.

As the bucket's **142** penetration of a material volume during loading normally is limited to a rather short advancement, typically 1 - 3 meters, and assuming that the ground surface is relatively flat, it can be taken that a simple plane surface model for the vehicle's position in the loading path will do, and that basing the model on this assumption will not contribute to more than marginal errors in comparison with the real ground surface. A linear equation for the ground plane model in immediate vicinity of the loading point *1221* with coordinates (Xc, Yc) can be written as:

$$X \cdot X_N + Y \cdot Y_N + Z \cdot Z_N = C \qquad\qquad (22)$$

An estimation of the coefficients **9821** X_N, Y_N and Z_N and the constant C can be obtained by means of the standard method of least squares with minimum 5 representative elements in the DTM **821** for a number of points on the current best model estimation $Z(3, n)$ of total area terrain surface in a vicinity of the vehicle loading point *1221*. In the actual application, it is no difficulty to get a sufficient number of measurements for the reference ground surface in such an area. The ground plane model Eq (22) coefficient estimations are performed dynamically in

the DTM-computer **82** when the vehicle **1** is on its way to the report point *1211* on the dynamic approach path *121*, where the loading path message **982** based on the actual terrain model Z(1, n) , n=1,2,... from the vehicle's current run is sent to the mission computer **6** for its optimization of the parameters **9312** for the dynamic loading path *122*. The mission computer then employs these coefficients **9821** from the message **982** for obtaining, for the loading path, the vehicle's expected heading, pitch and roll angles ψ_c, ϑ_c, and φ_c, respectively, specifically used as angular arguments of a transformation matrix $M(\psi_c, \vartheta_c, \varphi_c)$ needed for the loading process optimization, where Eq (3) is used to convert coordinates in the fixed to vehicle coordinate system *42* to coordinates in the fixed to ground coordinate system *41*. To obtain these angular arguments, the following model, in Eqs (23a), (23b), (23c) comprises the 3D vector position **X(s)** for a path from the loading point *1221* as a function of vehicle advancement s in the intended direction ψ_c and Eqs (24a), (24b), and (24c) for the corresoponding position **X(r)** at a lateral movement r in a perpendicular direction to the right on the same surface:

$$X(s) = \begin{cases} X(s) = Xc + s\,\cos(\psi_c) & (23a) \\ Y(s) = Yc + s\,\sin(\psi_c) & (23b) \\ Z(s) = Zc + s\,\tan(\vartheta_c) & (23c) \end{cases}$$

$$X(r) = \begin{cases} X(r) = Xc - r\,\sin(\psi_c) & (24a) \\ Y(r) = Yc + r\,\cos(\psi_c) & (24b) \\ Z(r) = Zc - r\,\tan(\varphi_c) & (24c) \end{cases}$$

Inserting (23a), (23b) and (23c) in Eq (22) gives a solution in Eq (25a) below for the angle ϑ_c. Likewise with (24a), (24b) and (24c) gives Eq (25b) below for the angle φ_c.

$$\begin{cases} \tan(\vartheta_c) = - [X_N \cdot \cos(\psi_c) + Y_N \cdot \sin(\psi_c)] / Z_N & (25a) \\ \tan(\varphi_c) = [X_N \cdot \sin(\psi_c) - Y_N \cdot \cos(\psi_c)] / Z_N & (25b) \end{cases}$$

Estimated loading height profile from the attack point 1222

Optimizing the parameters **9312** for the dynamic loading path *122* entails the parameters loading path depth, vehicle velocity and bucket **142** lift and tilt movement parameters. The optimization approach chosen in this invention is to employ the developing terrain model Z(1, n) from the vehicle's current running in conjunction with an actual best estimation Z(2, n) of the ground surface in order to be able to predict the outcome of various possible parameters for steering the vehicle and its implements. A principal idea is to keep the total model in the DTM computer **82**, and only to send over relevant information for the imminent needs of the mission computer **6**.

In practise, a two-dimensional height profile model of the terrain surface from the attack point *1222* along a vertical section through the linear loading path in the x/y-plane has been found to convey sufficient information for the optimization needs.

This loading height profile $Z_{load} = Z_{load}(S_g)$ data list **9822** is such a model. It is approximated, cf FIG 13, from layer 1 numbers $Z(1,n)$, elements n belonging to a subarea of DTM **821** involving a sufficient part of the pertinent material volume *181*. The height profile table $Z_{load} = Z_{load}(S_g)$ represents an average of estimated terrain z-coordinates in the fixed to ground coordinate system *41*, in a set of elements $\{n_{i,j}, j = 1,2,3,...,jmax\}$ inside a rectangular area centered around the forward edge of the bucket **142**, this edge being on horisontal distance $S_g = i \cdot d$ from the attack point *1222* for bucket's entry in the material volume at loading operation, and d is a suitable sampling distance between consecutive S_g numbers:

$$Z_{load}(i) = \sum_{j=1}^{jmax} Z(1,n_{i,j})/jmax; \quad i = 0, 1, 2, ... \qquad (26)$$

Determining the bucket 142 position in the fixed to ground coordinate system 41

In a loading movement the bucket **142** starts with its blade above but close to ground and penetrates the material volume *181*, at the same time as hydraulic pressure is increased on the lift cylinders **1411** in order to reduce ground friction from the weight of the bucket and its collected load. When a finishing lift can be expected to result in a full bucket, the penetration is halted. The loading movement concludes with the final lift of the bucket to get clear from the remaining material when returning with the load. A principal idea of this invention, in addition to having a good model of the material volume along the loading path, is to be able to control the bucket accurately during this movement by employing an accurate model of the bucket's geometry in a fixed to ground system as a function of vehicle advancement from vehicle loading point, and as a function of lift and tilt actuation of the load handling implement 14, as governed by a loading process sequential step variable k = 0, 1, 2, ... for controlling with good coordination each of these movements and actuations. It is also important to be able to predict the accumulated volume and weight of the pieces of material cut out from the material volume by the bucket, as well as the available bucket volume, in the various steps of a candidate loading process.

FIG 12 shows in a section the mechanics of the load handling implement **141** and the bucket **142** and frontal parts (one wheel and part of vehicle framework) from a loading vehicle.

For a number of progressive loading process states k = 0,1,2,..., the position of the bucket **142** can be predicted as the coordinates **X(k)** = [x(k), y(k), z(k)] in a fixed to ground coordinate system *41* for a number of points on the bucket geometry.

The geometry of the vehicle is in a first step determined in the fixed to vehicle coordinate system *42*. In a proceeding step these local coordinates [ξ(k), η(k), ζ(k)] are transformed to a fixed to ground coordinate system *41* by the following standard transformation equation.

$$\mathbf{X}(k) = \mathbf{X}(s) + [\xi(k), \eta(k), \zeta(k)] * \mathbf{M}(\psi c, \vartheta c, \varphi c), \quad k = 0,1,2,..., \tag{27}$$

For Eq (27), it is assumed that the origo of the fixed to vehicle coordinate system is located on ground level. The transformation matrix with the arguments ψc, ϑc and φc can be determined as:

$$\mathbf{M}(\psi c, \vartheta c, \varphi c) =$$

$$=\begin{bmatrix} \cos\vartheta c \cos\psi c & \cos\vartheta c \sin\psi c & \sin\vartheta c \\ -\cos\varphi c \sin\psi c + \sin\varphi c \sin\vartheta c \cos\psi c & \cos\varphi c \cos\psi c! + \sin\varphi c \sin\vartheta c \sin\psi c & -\sin\varphi c \cos\vartheta c \\ -\sin\varphi c \sin\psi c - \cos\varphi c \sin\vartheta c \cos\psi c & \sin\varphi c \cos\psi c - \cos\varphi c \sin\vartheta c \sin\psi c & \cos\varphi c \cos\vartheta c \end{bmatrix} \tag{28}$$

The steering angle is assumed to be zero and the local coordinate η for each point in the load handling implement can accordingly be considered to be invariant during the loading process. In order to obtain, as a function of loading process state k, the for the above transformation required local coordinates ξ(k), η(k) and ζ(k) for points on the mechanical structure of the load handling implement **14**, this structure can be considered as a number of partly linked rigid mechanical elements one being the bucket **142** itself and where a hydraulic cylinder can be modeled by a pair of rigid and both limited to move along a common straight line through two cylinder attachment pivots. In order to obtain how extending or contracting the cylinders will change the position of the bucket and assuming zero steering angle the mechanical structure can be quite accurately approximated by a structure in two dimensions, ξ (forward) and ζ (upward), in the fixed to vehicle coordinate system *42*. The rigid elements, consisting of planar bars and rods and the bucket represented by a polygon, are linked together by means of a number pivot axles perpendicular to the ξ/ζ-plan. Each pivot or polygon point can be represented by a unique integer from i = 1 to i = imax. Cf simplified model, FIG 13.

For each element j ∈ {E1, E2, ..., E4} belongs a number of such points which, due to the rigidity of the element and independent of the position of the element have constant distance to all other points on the same element. Locally, within the set of points belonging to the rigid element j these points can be represented by integers m = 0, 1, 2, ..., mmax(j). Specifically, m = 0 can be chosen to represent the center of gravity for an element and mmax(j) is the total number of pivot and polygon points in element j.

For the abovementioned points the ξ/ζ coordinates can be written as

$$\xi(j,m, k) = \xi \text{ -coordinate, loading process state k for}$$
$$\text{point m in the rigid element j} \tag{29a}$$

$$\zeta(j,m, k) = \zeta \text{ -coordinate, loading process state k for}$$
$$\text{point m in the rigid element j} \tag{29b}$$

Each rigid element E1, E2, ..., E8 is required to have, for defining the element's position and orientation, at least one pivot point and one additional index point. The latter must not neccessarily be a pivot point. For these two primary points we define

Pivot point, order number m = 1

Index point, order number m = 2

The table below shows a choice of pivot point, index and remaining points for the simplified load handling implement's mechanical structure **141** model. Cf FIG 12. The center of gravity points are not shown in the drawing and the bucket geometry defining points are not listed in the table.

Elements		Pivot and index points												Center of gravity points m=0									
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Vehicle frame	E0	X	X	X											x								
Main bar	E1			PIV	IND	m=3	m=4									x							
Rear rod	E2					PIV		IND	m=3								x						
Upper bar	E3							PIV	IND									x					
Front rod & bucket	E4					PIV			IND										x				
Lift cylinder, part 1	E5	PIV									IND									x			
Lift cylinder, part 2	E6			PIV								IND									x		
Tilt cylinder, part 1	E7		PIV										IND									x	
Tilt cylinder, part 2	E8						PIV							IND									x

In the two dimensional model of the mechanics **141** of the load handling implement the coordinates of the pivot and index points as functions of the extensions of the lift and tilt cylinders can now be determined by means of classic analytic plan geometry

The coordinates of the bucket **142** geometry position and orientation defining points can be determined in the same way as the already treated pivot and other points. Bu specifically employing a number of points on the inside of the bucket, the coordinates of these points can be used for determining the volume loading capacity of the bucket for any state k of the penetration and loading process. The bucket defining points can be represented by an integer number

sequence of m_{smax} numbers included among the total set of numbers representing the rigid element E4 in the simplified model. Thus for bucket geometry defining points:

$$m_s = 1, 2, ..., m_{smax} \qquad (30)$$

Employing Eq (27), the bucket defining points for each state k of the penetration and loading process can now be determined in the fixed to ground coordinate system *41* by the coordinate vector $\mathbf{X}(4, m_s, k)$:

$$\mathbf{X}(4, m_s, k) = \mathbf{X}(s) + [\xi(4, m_s, k), \eta(4, m_s, k), \zeta(4, m_s, k)]^*$$

$$* \; \mathbf{M}(\psi c, \vartheta c, \varphi c) \qquad (31)$$

As all bucket defining points can be placed in the ξ/ζ - plane of the fixed to vehicle coordinate system *42* , all $\eta(4, m_s, k)$ can be set to zero in Eq (31) above.

Estimation of the volume loaded, for a given vehicle 1 and load handling implement 14 loading path and movement

For optimizing, in any loading cycle, vehicle 1 and load handling implement 14 loading path and movement, it is needed to have a procedure and software for estimation of the volume loaded for any given such operation. The estimation can be based on the loading height profile data list 9822 which, for successive depths $S_g = i \cdot d$, i = 0,1,2,... of penetration, as counted from the attack point *1222*, represents an estimated height profile $Z_{load}(i)$, i = 0,1,2,... in fixed to ground coordinates of the material volume , as outlined above, Cf Eq (26). In a certain state k of the loading movement the edge of the bucket 142, can be expected to be located on a rather well-defined position inside the material volume. At this stage, a certain volume amount of the material volume then has been cut out by the forward edge of the bucket and been captured by the bucket. The volume amount thus cut out and captured depends on the movements and shape of the bucket and on the shape and properties of the material being loaded. Under the condition that the material being loaded is a relatively easy-running solid material, like sand, gravel or sufficiently broken down stone or other materials, the volume cut out and captured can be estimated with sufficient accuracy for each step of the loading process as a basis for an effective optimization of this process.

Let $\Delta V_s(k+1)$ be the volume cut out between the states k and k+1 of the loading process. Assume also that, in these states, the bucket 142 has not penetrated too deep in the material volume *181*. Consider a vertical cut of the material volume and oriented along the planned loading path. The near trapezoidal polygon "abcd" in FIG 14 represents a projection on this cut of the expected volume being cut out between those two states, k and k+1 of the loading process . The

upper edge "bc" of the polygon is part of a polygon through or approximating the sample points from the loading height profile data **9822**. The lower edge "da" of the polygon is part of a polygon through the bucket edge in its sequential s/z plane positions according to Eq (31) [$S_g(k)$, $z(4, m_g, k)$], k=0,1,2,... in the fixed to ground coordinate system *41*. Assuming that the bucket **142** cross-section is constant over its entire width B and that the polygon can be approximated by the trapezoid "abcd" the following equation holds for $\Delta V_s(k+1)$:

$$\Delta V_s(k+1) = \tfrac{1}{2} Bh \,[Z_{lappr}(k) + Z_{lappr}(k+1) - z(4, m_g, k) - z(4, m_g, k+1)] \qquad (32)$$

where

$$h = S_g(k+1) - S_g(k) \qquad (33)$$

and $\quad Z_{lappr}(k) = [S_g(k) - i{\cdot}d\,)/h]{\cdot}Z_{load}(i) + \{1 - [S_g(k) - i{\cdot}d\,)/h]\}{\cdot}Z_{load}(i+1) \qquad (34)$

where

$$i{\cdot}d \le S_g(k) < (i + 1){\cdot}d \qquad (35)$$

and

$$S_g(k) = \sqrt{[x(4, m_g, k) - X_{atac}]^2 + [y(4, m_g, k) - Y_{atac}]^2} \qquad (36)$$

Let $V_s(k)$ be the total accumulated volume amount cut-out, at loading process state k of the loading process, by the bucket's edge from the material volume:

$$\left\{ \begin{array}{l} V_s(k) = \displaystyle\sum_{r=1}^{r=k} \Delta V_s(r), \ k=1, 2, 3, \ldots \qquad (37a) \\[2mm] V_s(0) = 0 \hspace{5.5cm} (37b) \end{array} \right.$$

The bucket's **142** volume holding capacity depending on its orientation, cf FIG 15, can be estimated from the bucket geometry and the properties of the loaded material. In an effective loading movement the flat lower plate of the bucket is initially driven into the material volume very close to the ground. During the corresponding states of the loading process it is important, in order to reduce or eliminate bucket's ground friction, to allow for sufficient hydraulic pressure in the lift cylinder circuits in order to balance the empty weight of the bucket and the rest of the load handling implement mechanical structure. At the same time, the bucket should not be allowed to rise or tilt significantly which might force a premature abortion of the penetration. Gradually, as the penetration continues, bucket load from the received material is increasing. At that stage, support reaction forces might increase acting on the bucket and causing friction. By comparing the hydraulic pressure in the lift cylinder circuits with a desired pressure considering also the expected weight of the loaded material at state k, the hydraulic pressure can be adjusted in order to facilitate the penetration by reducing friction due to support reaction forces to a

minimum. Still it is important to keep the bucket low and not tilted. In this way the penetration can normally continue until the volume cut out equals the instantaneous volume holding capacity of the bucket. At this stage the penetration stops, but hydraulic pressure on the lift cylinder can now be allowed to increase further in order to lift the bucket. At the same time the tilt cylinders are engaged in order to increase the bucket holding capacity to its maximum before the bucket will raise above the upper edge of the material volume.

Bucket lift can continue until the bucket is free from the material volume. At this moment the return movement on a dynamic transport path *124* can be initiated, beginning during the first piece of the path by lowering the bucket to a low center of gravity transport position. In certain cases the conditions at penetration are such that the bucket starts to rise markedly before the desired bucket pressure can be reached. In this case the material density is probably lower than expected. The density parameter might then have to be changed. On the other hand if the material density is significantly higher than expected, the intentionally increased hydraulic pressure might not be sufficient in order to reduce friction causing slipping which also might lead to an unsuccessful loading attempt.

Estimation of required lift force and power during the loading path

The estimation is based on knowing, with reasonable accuracy, and for each state of the loading process, in the fixed to ground coordinate system *41*, the z-coordinate and mass of each of the moving elements. By knowing this, the potential energy of the system consisting of these moving masses can also be estimated. We can also assume that the vehicle is moving on a flat but not neccessarily horisontal surface according to Eq (22). With zero friction, the dynamic process of the loading movement consumes, in any time interval, an amount of energy equal to the work needed for lifting each of these masses. By differentiating the potential energy for each of these masses as a function of the state variable k, an estimation can be made of lower bound variables for the required lift forces and power needs.

As shown above, for each state k of the loading sequence, the 3D position, in a coordinate system fixed to ground, of the main elements of the load handling implement including the bucket can be estimated with fair accuracy. This also applies to each element's center of gravity.

As the shape of the bucket is known and by using the simple assumption that the upper surface of the volume cut out by and received in the bucket is flat and horisontal, also the fixed to ground coordinates of the center of gravity of the accumulated load in the bucket can be determined with reasonable accuracy. Obviously, also the weight of all elements of the load handling

implement are known and we have shown above in Eq (37) how the cut out and accumulated loaded volume $V_s(k)$ can be estimated. By using an estimate of the material density, $V_s(k)$ can be transformed to a weight estimation of the load in the bucket.

An expression for the potential energy at each sequential state of a loading process

Exploiting the symmetry of the load handling implement **14** and bucket **142** on both sides of the ξ/ζ-plane in the fixed to vehicle coordinate system, and assuming small roll angles and roll angle motions, the two dimensional model of the load handling implement **14** and bucket **142** and the above explained concepts can also be employed for estimating volumes, weights and centers of gravity.

For state k of the loading process, let $U_{mek}(k)$ be the potential energy of the mechanical elements of the load handling implement 14 with bucket 142, and let $U_s(k)$ be the potential energy of its received and accumulated load. Let $U(k)$ be the total potential energy in state k:

$$U(k) = U_{mek}(k) + U_s(k) \tag{38}$$

The control dynamics allows for the load handling implement **14** to be controlled from a sequential instruction flow with constant sample time TSAMP and thus $t_{k+1} - t_k = $ TSAMP invariant of k for the sampling instances $t = t_1, t_2, t_3, \ldots$ .Let $k(t_k)$ be the desired state at $t = t_k$ and let $\Delta U(k)$ be the work required to bring the system from state k to state k+1:

$$\Delta U(k) = U(k+1) - U(k) \tag{39}$$

A complete loading sequence typically requires some ten seconds from attack of material volume to ready for return movement, while the sampling time TSAMP ought to be in the order of some 0.1 s or less in order to keep the system within normally acceptable error margins. Considering unavoidable model errors due to approximations regarding material density and loaded volume shape, effects of kinetic energies not considered in the models etc, we can assume the power needed to be constant during each time interval $[t_k, t_{k+1}]$, k=0,1,2,3,... Let P(k) be the average power needed during such a time interval, and our assumption can be formulated as:

$$P(k) = \Delta U(k) / \text{TSAMP} \tag{40}$$

Eq (40) can be used for optimizing lift and tilt movement speeds in order to minimise total time for the loading process within the constraint of not exceeding available implement actuation power.

An expression for Umek(k)

Let M(j) be the mass of the rigid element Ej and let $U_{mek}(k)$ be the potential energy, in a fixed to ground coordinate system *41*, of the load handling implement's **14** mechanics **141** and bucket **142**, but excluding the load cut out and received by the bucket:

$$U_{mek}(k) = \sum_{j=1}^{jmax} gM(j)[z(j, 0, k) - z(j, 0, 0)] \qquad (41)$$

where g is the vertical acceleration of gravity

An expression for Us(k)

Let $U_s(k)$ be the potential energy, in a fixed to ground coordinate system *41*, of the load cut out and received by the bucket. Assume further that the center of gravity for the load is close to the center of gravity for the bucket:

$$U_s(k) = \rho \cdot g \, [z(4, 0, k) - z(4, 0, 0)]V_s(k) \qquad (42)$$

Where ρ is a measure of density representing the loaded material, in kg/m^3

Estimating the magnitude of the support reaction forces on bucket

When the bucket **142** is supported by ground and has to be moved laterally, a friction force acting on the bucket and oriented as to repel the movement is excited. The strength of this friction force is proportional to the support reaction forces on bucket. By estimating the magnitude of this force F(k) as a function of loading state k, it is feasible to control the hydraulic pressure in the lift cylinder of the load handling implement in order to minimise this support reaction force and load movement repelling friction forces and instead to increase the reaction forces on the front wheels of the loading vehicle in order to improve traction and reduce the risks of slipping wheels.

The work required to work against the support reaction force an infinitesimal distance h equals the work required to lift the load handling implement with bucket and load the same distance h. Provided that the latter work can be estimated, from this equivalence the support reaction force F(k), k= 1, 2, 3, ... can be obtained.

Let F(k) be the support reaction force in a state k. The work required to move against the support reaction force an infinitesimal distance h can then be expressed as $F(k) \cdot h$.

Let $\Delta z(j,0,k) + o_j(h)$ be the positive vertical movement in the fixed to ground coordinate system *41* required for the center of gravity of element j when the bucket itself is subjected to a positive

vertical movement h, corresponding to a work amount $[\Delta z(j,0,k) + o_j(h)] \cdot gM(j)$ for each element j. For the bucket, assuming as above that the center of gravity for the load is close to the center of gravity for the bucket, the corresponding work amount can be estimated by the expression: $\rho \cdot g \, [\Delta z(4,0,k) + o_j(h)] \cdot V_s(k)$.

From the above reasoning, $F(k) \cdot$ can be solved starting from the following difference equation as shown for the simplified load handling implement mechanical structure of the example in FIG 12, with element j=4 being the front end rod with the bucket fixed to it:

$$F(k) \cdot h = g \sum_{j=1}^{jmax} [\Delta z(j,0,k) + o_j(h)] \cdot M(j) + \rho \cdot g \, [\Delta z(4,0,k) + o_j(h)] \cdot V_s(k) \qquad (43)$$

where $\lim o_j(h) = 0 \cdot$ for h ---> 0,

and, introducing the geometry derivatives $[dz(j, 0, k_o)/dz(4, 0, k_o)]$; j = 1,...,jmax, Eq (44) results:

$$F(k) = g \sum_{j=1}^{jmax} M(j) \, [dz(j, 0, k_o)/dz(4, 0, k_o)] + \rho \cdot g \, V_s(k) \qquad (44)$$

Balancing the gravity of the load handling implement 14 during the loading process

As mentioned above, friction forces can be significantly diminished if the support reaction forces on the bucket can be reduced by balancing the load handling implement through proper application of hydraulic pressure in the lift cylinders. Let $F_1(k)$ be the force, in state k of the loading process, required to be exerted by the lift cylinder in order to balance the load handling implement including the expected gravity $\rho \cdot g \, V_s(k)$ cut out and received by the bucket. Assuming that the mechanical structure of the load handling implement can be considered stiff so that the work delivered by the lift cylinder can be delivered practically with no loss to relieve the support force F(k) as obtained from Eq (44), the following work equation (45) can be applied to an infinitesimal lift cylinder marginal extension Δl and the corresponding marginal movement h in the z-direction of the bucket **142**,

$$F_1(k) \cdot \Delta l = F(k) \cdot h + o(h) \qquad (45)$$

and by differentiation:

$$F_1(k) = F(k) \, [dz(4, 0, k)/dl] \qquad (46)$$

From this force estimate, a corresponding hydraulic pressure can be derived knowing the area of the lift cylinder pistons. By including, in the vehicle and implement control data list **971**, de-

manded lift cylinder pressure as derived from Eq (46), friction forces from support reaction can be substantially reduced and maximum weight transferred to the front driving wheels of the vehicle 1 to facilitate the part of the loading process where the bucket penetrates the material volume *181*.

Obstacle detection and avoidance

Reliable and accurate detection functions are needed for the safety of the environment, for human safety and for protecting the vehicle itself against accidents and damage due to collisions or maneouvers out of controlled paths, zones and enclosures. A system for obstacle detection requires sensors for detecting and recording occurring obstacles, at least their shape and position. This data must then be stored in a systematic manner, for allowing analysis and warning or emergency action based on the currently relevant collected obstacle data as well as regarding the vehicle's 1 actual shape and current and its nearest planned or predicted continued path. Primarily an object of a certain minimum size such as height appearing inside an obstacle free zone *191* as defined in the DTM **821** can be considered to be an obstacle. It can also be the purpose of an obstacle detection system to check the vehicle's actual position and its path so that it does not, neither is predicted to, enter any area not inside any obstacle free, loading or unloading zone.

From a point the vehicle 1 can be associated with a number of zones in a fixed to vehicle coordinate system. A first such zone can be the nearest environment around the vehicle where detection and occurrence of an obstacle requires immediate emergency stop. A second such zone can be an additional zone around the vehicle, but outside the first zone. Detection and occurrence of an obstacle in this second zone might only require a warning or/and a slowdown action. The size and number of such zones depends on the vehicle's speed, maneouvering capability, braking distance and the range of the obstacle detection system. Data regarding these zones can be conveyed in the mission instructions **9** in the form of zone, inner and outer, border polygon list 9521 and 9522, respectively. During operation, the DTM-computer **82** can employ this data together with from mission computer **6** obtained vehicle and implement control data list **971** for evaluating criteria based on data in the DTM **821** for warning or emergency action at occurrence of obstacle inside zone both related to the current position of the vehicle as its planned and predicted path according to the current vehicle and implement control data list.

In preparation of each path, both the vehicle control computer **211** and the DTM-computer **82** receive a vehicle and implement control data list **971**. In the DTM-computer an obstacle avoidance mapping *1955* in fixed to ground coordinates can be produced from projecting the fixed to vehicle obstacle avoidance zones on the fixed to ground coordinate system 41 for each position of the vehicle in its imminent path according to the vehicle and implement control data list **971**. This obstacle avoidance mapping *1955* can be considered as a set of elements in the DTM **821** being the union set of all elements occupied by some area from any of the projected vehicle obstacle avoidance zones on the fixed to ground coordinate system. Cf FIG 18. This enables an initial check before starting the vehicle in the path that this path will keep the vehicle well inside the allowed obstacle free, loading and unloading zones. When the vehicle is underway on its path, the DTM computer constantly checks if any obstacle appears at any element of the DTM which is covered by any area from any of the vehicle's obstacle avoidance zones as projected on the fixed to ground coordinate system for the actual position of the vehicle.

Let $P(K, L)$ be points and let $X(K, L) = [\xi(K, L), \eta(K, L), \zeta(K,L)]$ be the corresponding coordinate vectors in a three dimension coordinate table of the fixed to vehicle coordinate system *42* where the points $P(K, L)$ represent the vehicle's obstacle avoidance geometry *195* and for each of the levels $L = 1, 2,..., LMAX$ consists of a fixed to vehicle obstacle avoidance zone $\mathcal{A}(L)$, *1951*, contained within a closed border polygon $\omega(L)$ *1952* with its corners being the points $P(K, L)$ for $K = 1, 2, 3, ..., KMAX$.

Let $X(s) = [X(s), Y(s), Z(s)]$ be coordinates and $\psi(s)$, $\vartheta(s)$, $\varphi(s)$ be heading, pitch and roll angles in the fixed to ground coordinate system *41* for the fixed to vehicle coordinate system *42* in a point $P(s)$ located on a distance $s - s_0$ along the vehicle's planned path from its current position with its coordinates $X(s_0)$, where this vehicle path is defined by a vehicle and implement control data list **971** from the mission computer **6**. Let $A(L, u)$ be an obstacle avoidance zone projection *1954* on level L of the fixed to vehicle obstacle avoidance zone $\mathcal{A}(L)$ on the DTM **821** in the fixed to ground coordinate system, where this zone $A(L, u)$ is contained within a closed border polygon $\Omega(L,u)$, *1953*, as defined by points $P(K, L, u)$, and their corresponding coordinate vectors $X(K, L, u) = [X(K, L, u), Y(K, L, u), Z(K, L, u)]$, $K=1, 2, ..., KMAX$ and where each such point $P(K, L, u)$ is a projection on the DTM in the fixed to ground coordinate system *41* of the point $p(K, L)$ with the coordinate vector $X(K, L) = [\xi(K, L), \eta(K, L), \zeta(K,L)]$ belonging to the border polygon $\omega(L)$ in the fixed to vehicle coordinate system *42*. Finally, a fixed to ground obstacle avoidance mapping *1955* is made up as the union set $\Theta(L,s)$ of all ob-

stacle avoidance zone projections A(L, u) from the vehicle's different positions "u" along its path, $s_0 \leq u \leq s$.

Four steps to obtain the fixed to ground obstacle avoidance mapping *1955*:

1° Let P(K, L, u) be the projection on DTM **821** in fixed to ground coordinate system *41* of the 3D coordinate point *P*(K, L) in the fixed to vehicle coordinate system *42*. Let P(K, L, u) have the coordinate vector **X**(K, L, u) = X(K, L, u), Y(K, L, u), and Z(K, L, u)]. This vector can be obtained from Eq (47) below, where X(u), Y(u) and ψ(u) are, in the fixed to ground coordinate system *41*, 2D position coordinates and heading angle, respectively, for the fixed to ground coordinate system *42* according to vehicle and implement control data list **971**:

$$\mathbf{X}(K, L, u) = \mathbf{X}(u) + \mathcal{X}(K, L)^*\mathbf{M}[\psi(u), \vartheta(u), \varphi(u)] \tag{47}$$

the matrix M is defined in Eq (2) and the pitch and roll angles can be estimated from the DTM from the Z-coordinates of a number of elements in DTM around the element occupied by [X(u), Y(u)] and by using a standard least squares estimation like the one employed for finding Eq (22) coefficients, X_N and Y_N. From thus estimated X_N and Y_N for the point on [X(u), Y(u)], ϑ(u) and φ(u) can be obtained from the equations (25a) and (25b).

The Z-coordinate can be obtained directly from Eq (22) as Z(u) = [C(u) - X(u) X_N(u) - Y(u) Y_N(u)]/ Z_N(u).

2° The polygon Ω(L,s) is made up by X and Y coordinate points from the coordinate vector **X**(K, L, u), K=1, 2, ..., KMAX.

3° The obstacle avoidance zone projection *1954* A(L,u), is the surface within the closed polygon Ω(L,u). Elements of the DTM with some area inside the Ω(L,u) are considered to belong to this zone projection.

4° A fixed to ground obstacle avoidance mapping *1955* is represented by the union set Θ(L,s):

$$\Theta(L,s) = \bigcup_{u = s_0}^{u = s} A(L,u) \tag{48}$$

The obstacle avoidance assignment of the DTM-computer **82** is, with a predetermined rate to analyse the DTM **821** inside areas Θ(L,s), L=1,...,LMAX, and carry out those actions possibly following the obstacle avoidance analysis according to the criteria listed below. In addition, for each new vehicle and implement control data list **971** the DTM has to evaluate it according to the criteria below for possible conflicts with established obstacle free. loading and unloading zones.

1° If, for any element in DTM $Z(4, n) = 1$ and this element is also within $\Theta(L, s_0)$, but given threshold value H is exceeded by $H \leq Z(1, n) - Z(2, n)$ for this element, then there is at least one element of DTM within level number L of the fixed to ground obstacle avoidance mapping *1955* that has to be considered as an obstacle requiring obstacle avoidance action with message number H(0, L).

2° If, for any element in DTM $Z(4, n)$,$Z(5, n)$ and $Z(6\ n)$ all are zero and if this element also is within $\Theta(L, s_0)$, at least one point of the fixed to ground obstacle avoidance mapping *1955* number L is not located inside any of the obstacle free, loading or unloading zones. This event requires obstacle avoidance action with message number H(0, L).

3° If, for any element in DTM $Z(4, n) = 1$ and this element is also within $\Theta(L, s_0)$, but given threshold value H is exceeded by $H \leq Z(1, n) - Z(2, n)$ for this element, then there is at least one element of DTM within level number L of the fixed to ground obstacle avoidance mapping *1955* that has to be considered as an obstacle in the planned path requiring obstacle avoidance action with message number H(1, L).

4° If, for any element in DTM $Z(4, n)$,$Z(5, n)$ and $Z(6\ n)$ all are zero and if this element also is within $\Theta(L, s)$, at least one point of the fixed to ground obstacle avoidance mapping *1955* number L is not located inside any of the obstacle free, loading or unloading zones. This event has to be considered as a cause for rejecting the planned path requiring obstacle avoidance action with message number H(1, L).

Obstacle avoidance messages from the DTM-computer at an inner obstacle avoidance geometry J=1 and an outer obstacle avoidance geometry J=2:

H(0, 1): Emergency stop message **9841** to the vehicle control computer **211**

H(0, 2): Warning message **9842** to the vehicle control computer **211**

H(1, 1): Rejection of planned path in revision message **980** to the mission computer **6**

H(1, 2): Warning message **9842** to the vehicle control computer **211.**

Other aspects, objects and advantages of the present invention can be obtained from a study of the drawings, the disclosure and the appended claims.